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Impact of high energy heavy ion nuclear collisions on advancement of nuclear physics

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Abstract : The contributions of low energy heavy ion research to the inventions in nuclear physics are highlighted The theoretical ideas used in their interpretations are qualitatively discussed The survey of the literature relevant to the seminar topic is presented The light projectile collision work and its relevant physics is briefly summarized In light of this, few suggestions are made to effectively use our heavy ion facilities

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1. Introduction : Achievements

The thrust of nuclear physics research has been along the four fronts : (a) To push forward the horizon of known atomic elements and unfolding their structures, (b) To discover new reaction mechanisms and interpret them in physical pictures as demanded by the challenges in the first goal, (c) To study strong nucleon-nucleon interaction and its relation to effective interactions and nucleus-nucleus interactions, (d) To use nuclear physics knowledge and facilities as probe to learn more about other areas of physics, such as condensed matter, atomic and particle physics. Even though this seminar is not on all the four aspects, it may be useful to recollect the important achievements in all the four.

The attempts to enlarge the chart of elements and their isotopes as far out of the beta stability lines as possible have been very successful [1]. In the efforts of producing superheavy elements we synthesized new heaviest elements $Z = 107–109$. The work aims at answering the basic question. "What are the maximum value (N_{mx}) and the minimum value (N_m) of neutron number so that all the isotopes (N, Z) of an element Z having $N_m \leq N \leq N_{mx}$ are bound ?" A curve obtained by joining the points (N_{mx}, Z) for all the elements Z would give the neutron drip line on the chart while the curve obtained from joining (N_m, Z) points on the chart would give the proton drip line. Naturally it follows that the neutron binding energy and proton binding energy on their drip lines are nearly zero. This puts an end to discovering particle of stable nuclei beyond the drip lines on the nuclear chart. Today we know part of the proton drip line upto $Z \leq 20$ and to some extent in the $A = 100$–160 region ($Z > N$), while the neutron drip line only upto $Z > 8$. We are hopeful of getting the proton drip line while neutron drip line discovery will be much harder to achieve. The distance of neutron drip line from the edge of the stability line increases monotonically with Z. Nuclear stability is governed by strong interaction decay modes, the nucleon, alpha, heavy cluster and fission. Nuclear decay mode being the fastest, controls its stability. In this achievement, development of accelerators, sophisticated instrumentation and detectors and a variety of rare beams and targets of high purity, have played the important rôle. Identifying these elements and isotopes, whereever possible, their decay and spectroscopic studies were carried out. It revealed new information which was not possible before. We found new exotic decay processes such as delayed proton and fission, proton and heavy cluster decay from the ground states. The spectroscopic study of the new elements brought some surprises. Their low lying spectra revealed new magic numbers corresponding to $A = 100$ ($N = Z = 50$) and $A = 132$ ($Z = 50$, $N = 82$) in the spherical regions and $Z = 38$, $N = 38$ in the deformed regions. The grand old shell model magic numbers and collective liquid drop model were invented for the understanding of the properties of nuclei in the beta stable valley. Now same basic ideas seem to work for nuclei between the edge of stability and the drip lines, giving different doubly closed shells and deformed regions. Besides this their spectra show the coexistence of different nuclear shapes superdeformed bands, signature splitting and identical bands all in the same nucleus which were never imagined before.

The grand old fission process produced many nuclei far off the stability. Later multi-nucleon transfer reaction was successfully utilized to populate neutron rich isotopes in Uranium, Actinide, and light mass regions, inaccessible to fission. The high energy collisions undergoing fragmentation and spallation produced nuclei far off the stability edges towards the proton and neutron drip lines. With the availability of many different types of beams, fusion reaction played an important role along this direction. It has produced neutron deficient isotopes of medium and heavy nuclei. The greatest deficit is produced by fusing nuclei with close Z and A values and using lighter stable isotopes as target and projectile. However, fusion materializes best when target and projectile system is asymmetric, they yielded $Z = 107$–109 elements. The symmetric collisions gave products yielding greatest neutron deficient nuclei. Such fused system decays by 1–3 proton or alpha emissions than neutrons. While asymmetric fused system emits 2–3 evaporated neutrons. Delayed proton emission, delayed fission and alpha decay are some of the exotic reactions found from the study of neutron deficient nuclei. Understanding ot these different reaction mechanisms and developing them to the level of qualitative understanding are the theoretical challenging problems. This seminar deals with some of the problems. We have the qualitative understanding of single nucleon transfer reaction and fusion process in sub- and near-barrier energy region.

It was only in early period of nuclear physics that emphasis was on nucleon-nucleon collision to learn about basic inter-nucleon interaction over the range of energies upto pion threshold. Later meson-nucleon interactions were studied to gain further inside into the problem. The effective interactions were studied from Brueckner-Bethe theory. It provided the foundations to shell model at a qualitative level. Today the fruitless QCD based ideas being used, nothing has come out from these efforts beyond very qualitative understanding of the interaction properties. Using heavy ions to understand nucleus-nucleus potential is, to me, a frutile approach. It can certainly be used to parametrize the experimental data. Even that will be meaningful only if it does not vary much with the incident energy E, and target-projectile mass. One can certainly use it to extract physical picture behind the broad features of the observed data.

Thermal neutron interactions were first used in the study of solid and liquid properties. Later we noticed the emergence of implanted ions in the study of electric and magnetic field gradients in materials using the known quadrupole and magnetic moments of implanted ions. Channeling of light ions was used to study single crystal impurities and defects. Heavy ions are now the regular probes in the study of changes in the physical and chemical properties of materials and thin films. These changes are caused by the damages they produced. Heavy ion collision with atoms has been the active field during the recent past. It brought out information about exotic atoms of importance in astrophysics which would have been inaccessible to us otherwise. Nuclei had played an important role in the past in testing the theory of weak interactions. Recently, nucleus has become the laboratory for studying nonperturbative QCD effects. The end of beta decay energy is of importance to determine neutrino mass. While double beta decay, mirror nuclear energy levels are of utmost use to test the theories of weak interactions and to search their violations and strong interactions symmetries. Nuclei whose structure is simple and reliably known along with the transition matrix elements such as isomultiplasts and Fermi and GT transition matrix elements fall in this category. The nuclear reactions and their cross sections, particularly exothermic, has been the elder sister of astrophysics. Today we still do not know cross section of reactions particularly at low E and of heavy ions that are of importance in astrophysics.

2. Nuclear reactions

All the above achievements were possible because of the use of different types of reactions that were effective in populating different nuclear isotopes. The aim of heavy ion collision studies today is : (a) To discover all the isotopes upto neutron and proton drip lines for all the known elements. (b) To measure their masses and study the decay modes and life times. (c) To carry out their spectroscopic studies. Part of this goal is achieved by using different reaction mechanisms for their production in different mass regions. (1) The light and medium ion induced fusion mechanism is effectively used in producing neutron deficient nuclei in medium mass region. (2) Light and medium ion induced multi-nucleon (cluster) transfer reactions were used in synthesizing neutron rich isotopes of heavy elements. (3) High energy proton spallation reaction yielded exotic isotopes of light mass elements. (4) The high energy projectile fragmentation effective in producing very neutron rich isotopes of light and medium heavy elements.

What is the difficulty in fulfilling this aim of heavy ion research ? Reactions used to obtain nuclei far off stability are endothermic, hence require higher beam energies, besides the Coulomb barrier also increases faster with heavier projectile-target combination. At such beam energies, the number of open channels producing many other elements and their isotopes near the stability line increase fast. The cross sections of these reactions are orders of magnitude larger than reaction channels producing exotic nuclei far off the stability lines. In the fusion reaction producing these exotic nuclei, the compound nucleus (CN) has many tens of MeV excitation energy. It deexcides by the emission of neutrons, charged particle and gamma rays. The daughters decay by beta, nucleon and alpha emissions. In the process the product consists of large variety of nuclei. In these reaction products to separate out specific exotic nucleus produced with very small cross section (1% of the total reaction cross section) relative to that of other products requires special reaction channel selectors and detection techniques.

The elements of half-lives down to m sec-μ sec and of very small cross sections cannot be separated from 10^{20} times more abundent target and catcher nuclei by online isotope separator system. For their identification, heavy ion accelerators, isotope separator on line, recoil mass separator facility with focal plane detectors and time of flight measurement through spectrometers, sophisticated beam optics supported by advance radiation detectors are essentials. The recently discovered decay modes of nuclei far from stability and their low spin spectroscopic properties are made possible because of on line low temperature nuclear orientation refrigerators [2] to isotope separators on line with accelerators and the recoil mass spectrometers. Nuclear orientation refrigerators with Compton polarimeter made it possible to measure spins, parities and multipole mixing ratios of excited states in these exotic nuclei. The angular correlation studies (such as alpha-beta) gave information about nuclear-shapes and decay properties. Nuclear shape coexistence in $I^{118-120}$, large deformations in Ce^{124} sudden change of shape from very large prolate to oblate between $N = Z = 38$, 36 and nuclear shape dependence of alpha directional correlation came out from these efforts. The temperature dependence of angular anisotropy of radiation emitted from oriented nuclei yielded information of nuclear moments of ground state density distributions and isomeric states and with NMR J of parent state, spectroscopic information on the levels in daughter nucleus and alpha-beta decay dependence on nuclear shapes. Nuclear orientation is advantageous because of its large data accumulation capacity in much shorter time. Properties of very weak < 1% transitions and weakly populated states < 1% even in very complex decays are measured with this technique.

3. Nuclear spectroscopy

The current trend in nuclear spectroscopy is to extend the knowledge of the structure of nuclei near stability edge to nuclei far out near the drip lines. The efforts yielded results such as, the discovery of new decay modes, unexpected new magic nuclei both in the spherical and deformed regions, observation of high spin excited state of $J \simeq 65$, superdeformed bands of $\beta \simeq 0.6$, signature splitting, identical bands, and excitation of giant resonances. Almost all the nuclear daughter structure information is obtained from electromagnetic and weak interactions as it should. Because of strong interactions, reactions played only supplementary role.

In the fusion of two nuclei, the cross section of the production of nucleus far off stability is generally 1% of the total reaction cross section as said before The traditional in beam spectroscopy of such a nucleus is impossible. To unscramble the gamma rays in such an event recoil spectrometer (RMS) tag is not sufficient. The 5 Neutron multiplicity filter covering 2π solid angle was placed in the forward direction and 4 NaI detectors specially built for detecting protons and alphas were placed at 90°. Then RMS–*n*–*r*, RMS–*p*–*r*, *n*–*r* and *n*–*n*–*r* were detected. The Delta *E*–*E* detector at the focal plane of RMS enabled one to measure *Z*. In the inverse reaction RMS–Delta *E*–*r* coincidence was used.

4. A brief review of nuclear collisions

A nuclear reaction (including inelastic and elastic) is classified into compound nucleus (CN) and direct nuclear (DI) reactions [3,4]. In the CN reaction, it is assumed that a compound nucleus, as a composite system of projectile and target, is formed. This CN is formed in an excited state after going through large number of states in many collisions before it reaches the statistical equilibrium. At this stage no nucleon has energy large enough to escape While in DI the target-projectile initial state changes to final state of outgoing particle-residual nucleus in a single collision. The time scale of the single collision DI reaction is of the order of the projectile transit time $\sim 10^{-23}$ sec. While in CN reaction it is $\sim 10^{-17}$ sec, million times longer. Because of which the intermediate state CN energies are sharply defined and $\sigma(E)$ changes very rapidly whenever the excitation energy coincides with these sharp energies. On the other hand the DI $\sigma(E)$ are slowly varying function of *E* as virtual state energies are not sharply defined. The DI reaction is a simple peripherical while CN is a complex volume reaction. In DI collision, the initial and final states have good overlap with minimum rearrangement of nucleons and few degrees of freedom. On the contrary CN reaction is complex and has no direct overlap of initial and final states. However, it maintains conserved quantities and its formation and decay are independent.

Both these processes contribute to a reaction in a particular channel. Although one is much faster than the other, because these time scales are small compared to experimental resolution. Since particles cannot be distinguished, they independently contribute to the cross section. From the above discussion, it follows that the CN contribution of the correlation function is symmetric about 90° while in DI, the symmetry axis points in the recoil direction. Generally, the region where both contribute, is rather narrow, because the density of states of CN increases rapidly with E, due to which σ_{CN} falls faster. Naturally, experimental data corresponding to each CN state contribution to $\sigma(E)$ will be difficult to measure. Besides, it will not show insight of the physics of the reaction mechanism or of the structure because of their complexity. Depending on the beam energy spread, energy resolution of the detector and target thickness one may find fluctuations in $\sigma(E)$ arising from CN contribution. The question is how to separate it into DI and CN contributions so that it can be made amenable to theoretical analysis. All the open channel reaction cross sections of same order of magnitude are measured. Their averages over an energy interval $(E, E + \Delta E)$, for $E >>$ average spacings of CN energy levels, are obtained. The deviations from these means and the averages are used to separate each channel cross section $\sigma(E)$ into DI and CN reaction contributions. They are analysed in terms of the statistical theory of nuclear reactions. From this method of separation, it is clear that with the increase of E, CN contribution to a specific channel goes down because many more channels open up and at such excitation in CN the level density increases. In light mass region and if its excitation energy is not too high CN contribution would show a resonance structure, because of their descrete level spacings. Polarization does not take place in CN reaction.

The typical DI reactions are stripping, pick up, multi-nucleon transfer, inelastic scattering and elastic scattering. Because of the complexity of the nuclear reaction theories, practical calculations and physical interpretation of the DI data is carried out using optical models. The channel potentials are adjusted to fit all the available data. Such analysis is valuable if the potentials are smooth and vary slowly with E and A. Such an approach ignores the detailed structure of nuclei except potential radius and surface thickness. Therefore it gives gross features of $\sigma(\theta, E)$. It is valid when few strongly coupled channels are weakly coupled to other non-elastic channels. It is likely to be more successful for medium and heavy nuclei. Absorption and polarization mainly take place at the surface.

There are many other reaction mechanisms or processes that take place in the collision of two nuclei. Their characteristic time scales lie between 10^{-23} sec to 10^{-17} sec. They are termed as incomplete CN reactions. At very high energies, nucleus appears more as group of individual nucleons, where time scale is shorter than 10^{-23} sec, and none of these mechanisms are valid. The reaction looks more like superposition of NN collisions as in knock out reaction which gives nuclear momentum distribution. At the other extremes of time scale less than 10^{-17} sec, where again all these approaches fail, and new mechanisms of cold dinuclear system and deep inelastic process take place.

Among all the possible reaction mechanisms, whichever is simple and reliable is used to extract the nuclear structure information.

5. Heavy ion elastic, inelastic and transfer reactions

5.1. Light ions [3,4]

The light ion induced reaction results are as follows : At low E, below the barrier elastic scattering is the Rutherford scattering caused by the known Coulomb interaction which is modified by finite charge distributions of **nuclei.** At such energies, at the higher end, inelastic Coulomb excitations are also caused by the same potential. Because of this and the simplicity of the DI reactions, they are used to obtain nuclear structure information related to charge distributions and transition moments. At a little higher energy, the projectile feels the surface tail of the nuclear potentials, and the nucleon transfer process becomes of equal magnitude. If the projectile nucleon is loosely bound and these channels are not strongly coupled this DI is simple and accurate enough to be used in deriving structure information. We know that they gave information about unfilled levels of the residual nucleus and filled levels of the target nucleus. The energies, J and spectroscopic factors of these levels are derived from the measured $\sigma(\theta, E)$. The extension of this mechanism to multi-nucleon transfer showed the importance of multi-nucleon correlations in the nuclear surface region.

In the light ion transfer reactions at $E \simeq E + 10$ MeV, number of partial waves contributing to the cross sections is not large, hence $\sigma(\theta, E)$ shows moderate amount of structure. Any one step reaction, such DI, $\sigma(\theta, E)$ exhibit forward peaking expected from linear and angular momentum conservation when it proceeds in nuclear surface. The position of the first and main peak or the shape of the forward part of $\sigma(\theta, E)$ provides the clear signature of l-transfer. Reactions with large Q-values lead to preference for many more values of l-transfer where $\sigma(\theta, E)$ is structureless. At high E, forward peaking of $\sigma(\theta)$ is more marked and have no structure to distinguish l-values. The interference of DI and multistep give ordox shapes of $\sigma(\theta)$.

5.2. Heavy ions [3,4]

Because of large mass heavy ion of a moderate velocity carries large momentum k, energy $E = k^2/2\mu = 1/2\mu v^2$ and large angular momentum l. The compton wave length $\lambda = 1/k$ is very small, therefore, its motion can well be described by semiclassical or classical approximations depending on its energy E. At these energies in heavy ion (HI) collisions many open channels are available. Hence strong absorption in optical potentials. All these being direct reactions and inclusion of many channels is difficult, one uses optical models for their cross section analysis. The heavy ion elastic, inelastic and transfer amplitudes f_t (θ, E) are generally oscillating functions of θ with rich variety of structure arising from strong absorption. The general philosophy is to reduce it to a number of sub-amplitudes, each of which behaves smoothly (in modulus) and is associated to classical physical process both in ray and wave optics. In a reaction in which large values of l contribute, $f(\theta)$ is splitted as the sum of contributions coming from the near side and far side of θ. Their behaviour and relative importance give rise to phenomena such as Freunhofer scattering, Fresnel diffraction, Rainbow scattering and Shalow scattering, when the absorption is strong.

(a) Elastic collision

In the elastic scattering of heavy ions Freunhofer diffraction minima arise due to their destructive interference when $E >> V$ (Coulomb) $= V_c$ in the region $\theta > \theta_c$ $(b(\theta_c) =$

$R_1 + R_2\psi$) the separation of these minima are at $\Delta\theta = \pi/kR$, ($R = R_1 + R_2$, R_i the nuclear radii). At low values of E, the coulomb potential is important, and the interference of a direct Coulomb $f_c(\theta)$ and far side diffracted ray gives rise to Fresnel diffraction in the region. The refractive effect of nuclear attractive potential at the surface is to pull the flux towards smaller angles.

When the absorption is not strong, the analysis of the experimental data is done in the optical model frame work with WKB approximation since large values of partial waves l are contributing, or by paratrizing the scattering matrix directly, $S_l(\delta_l(k), \eta_l(k))$. Optical model analysis is simply a way of optimum parametrization of measured cross sections.

The smooth part of elastic scattering $\sigma_e(\theta, E) / \sigma_R(\theta, E)$ is unity upto θ_c and fall exponentially thereafter due to strong absorption in the $\theta > \theta_c$ region [θ_c : scattering angle in presence of V_c corresponding to impact parameter $R = R_1 + R_2$].

(b) Inelastic scattering

The HI inelastic scattering differential cross sections provide information about angular momentum and parity transfer to the target. The trajectories corresponding to angular momentum $1 << 1g$ (g-indicates grazing impact values) are removed because of the strong absorption in HI. The waves corresponding to $1 >> 1g$ do not interact or only Coulomb excite the target. Therefore $\sigma(\theta$, incl) mainly comes from the grazing trajectories. The Freunhofer diffraction minima also occur at higher E but they are less deep and the first peak moves towards larger values as l-transfer increases. These oscillations are out of phase with those in elastic scattering if l-transfer is even and inphase for l-odd transfer. The values of l corresponding to $\theta < \theta_g$ (*i.e.* $l > l_g$) fall in the classically forbidden region and therefore are confined to nuclear surface in the inelastic scattering. Therefore position of this peak and its shape give the l-transfer value. Because of the transfer of some of its angular momentum, its l-value decreases and it has better chance to scatter in this range of θ-values. At lower energies, V is important and the contribution of nuclear potential V_n is confined to grazing trajectory. There is a featureless peak at $\theta = \theta_g$ in $\sigma(\theta$, incl) due to this. The waves corresponding to $l < lg$ *i.e.* $g\theta > \theta_g$ are strongly damped. Therefore, the point charge $f(\theta)$ at smaller θ is modulated by Fresnel diffraction at the edge of the absorbing region. These oscillations are in phase with the elastic scattering. In general, in HI collision, leading to inelastic channel, large values of l contribute to the cross section. While in light ion collision leading to inelastic process few values of l (only one or two) contribute to the cross sections.

The barrier top resonances arise when real $V(r)$ has a deep pocket and hence a large barrier. Further there has to be a strong absorption within the pocket but weak or no absorption near the barrier top, which implies surface transparency. In order to reduce the reflection, the absorption edge has to be fuzy. Such a potential supports a series of resonance states with $Re(E_\mu) \simeq E_B$ (Barrier). The width is proportional to the curvature of V at R (Barrier) and it increases with surface absorption.

(c) Nucleon transfer

The heavy ion single nucleon transfer (stripping and pick up) below the barrier energy $E < E_B$ (aA) and E_B (bB) are called sub-Coulomb transfer $(a + A \rightarrow b + B)$. Naturally, the CN formation probability is small therefore only DI contributes to the reaction cross section. Besides, the Coulomb effects are either small or can be calculated accurately. Therefore, $\sigma(\theta$: trans) can be reliably calculated if nuclear interaction is known with some confidence. Then it could be used to test nuclear models. It is not sensitive to optical model parameters. The cross sections are featureless almost independent of l. They increase monotonically to maxima at $\theta = 180°$. As E increases upto and above E_B diffraction peaks begin to appear at forward angles and grow untill they dominate $\sigma(\theta, E)$ peak at $\theta = \theta_g$ and develops into a bell shaped distribution in θ. At such E, P-stripping, N-pickup and charge exchange leading to same light element isotopes are similar.

The transfer amplitude is largest when initial and final orbits touch with the same distance of closest approach. When there is large difference between $\left(l_{gi} - l_{fi}\right)$ $(i, f$: initial and final channels) transitions with small value of l-transfer are inhibited. Good matching between entrance and exit channels results in localization of l-transfer (l_{tr}). The values of l_{tr} are determined by E and Q-values and mass transfer of that channel k. There is a range of Q-values that are optimum for a particular l_{tr} in a given reaction. This range is known as Q-window. The spin flip transitions are favoured for spin independent nuclear interaction, because the l_i and l_f matching requires them to be in opposite directions. When all elastic, inelastic and transfer channels are strongly coupled, which is the case in sub-barrier and near barrier energies, coupled channel calculations are to be carried out within the optical model frame work. The number of unknown coupling potentials are minimized using the approaches followed in nuclear structure while introducing internal degrees of freedom. This approach is followed in fusion reaction analysis below and near the barrier. When the coupling between the channels is weak DWBA is followed.

(d) Multinucleon transfer

The heavy ion multi-nucleon transfer cross sections are difficult to measure because in this (l, E) region, elastic and inelastic channels are also open and their cross sections are larger by orders of magnitude. To overcome this difficulty, magnetic spectrometer with good focal plane detector combined with the time of flight measurement or nano-sec resolution is required so that nuclear charge Z, mass A, ion charge q and energy E of the recoiled nucleus is precisely known. The coupled channel calculations are difficult, and absolute cross sections are not accurate.

For lighter projectile, multi-neutron pick up cross sections are larger for neutron rich target. In ^{14}N and ^{15}N projectiles transfer cross sections of 1 to 3 neutrons are measured. It increases with target mass due to increase in neutron binding B_n and larger radius. The $\sigma(\theta)$ of these quasi-elastic processes peaks around θ_g. Its main features are determined by l-transferred. They excite high-J states, populate nuclei away from stability valley, sensitive to relative phases of transferred nucleon wave functions and are strongly dependent on cluster correlations. Let us define l_{cr} as that angular momentum value at which the effective barrier just vanishes. Depending upon whether $l_{cr} > l_g$ or $l_{cr} < l_g$, the quasi-elastic nultinucleon transfer takes from trajectories corresponding to $l > l_{cr} > l_g$ or deep inelastic scattering from orbits $l > l_{cr} > l_g$. In the later case, the nuclear surfaces overlap and nuclei strongly interact leading to total kinetic energy dissipation. The cross section $\sigma(\theta)$ accordingly varies systematically. The maximum at $\theta = \theta_g$ widens as elasticity rises and the peak shifts to smaller angles. And finally in deep inelasticity region this transfer $\sigma(\theta)$ exponentially decreases falling further with the increase of nucleon number transfer. Deep inelastic transfer accompanied by the emission of charged particle, charge exchange and fragmentation leads to neutron rich nuclei.

(e) Sub-barrier fusion

Why the sub-barrier fusion is important ? One expects that at such energies elastic, few inelastic and nucleon transfer channels only will be open. Therefore, these few coupled channel theory can be used to test nuclear reaction model and to extract nucleus-nucleus interaction without further change of optical potentials. As pointed out earlier the number of channel coupling potentials are reduced by extrapolation of elastic channel potentials to include internal degrees of freedom following nuclear structure and fission philosophy. It is found that tunneling through the real barrier is insufficient to reproduce fusion cross sections. The tail of the imaginary potential extending out under the real barrier is necessary. One can test whether the fusion is a CN process, as the fusion cross section would then be independent of initial channels. This is done using different projectile-target combination leading to the same CN nucleus at the same excitation energy. After checking its reliability the nucleus-nucleus potential upto turning point could be derived from fusion cross sections. At higher E, the products of fusion nuclei has protons, neutrons, gamma rays, alphas, recoiled parents and daughters. At these E fission is negligible. The 90% of these products are in few degrees of the beam axis. Thus the background is 11 to 12 orders of magnitude larger to a rare event one wants to select.

With decreasing E, the σ (inelastic) and σ (trans) falls off much more slowly than σ (fusion). Therefore these coupling strongly effects σ (fusion). While at the barrier energies σ (fusion) starts to exceed them.

From the above review it is clear that charged particle reaction channels which are rare such as fusion, exotic residues and multi-nucleon transfer, are extremely complex to select and isolate. If further we want to carry out spectroscopic studies it is even more difficult. These are certainly the problems we should be doing. But can we do it ? Do we have facilities and dedication ? You can have your answers. My honest answer is we cannot do it because we neither have the facilities nor that dedication. But my sincere suggestion is that we should put all our efforts together including manpower and facilities, and judiciously choose a region of (Z, A) and carry out all kinds of observations that we can, on all their isotopes. We then analyse the data together and present a wholesome picture of what we learned from this work. Can we do this ?

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